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# JPL ADVANCED SOLAR SIMULATOR

# DESIGN TYPE A

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# I. INTRODUCTION

The need for improved space environment simulators at JPL has led to a new concept in solar simulator design. This new system concept derived from JPL work begun in 1960 when the solar simulator requirement for the 25-ft space chamber was established. Several variations of the basic system have been studied; the performance of the 25-ft simulator at JPL has been analyzed; and surveys have been conducted of the problems encountered by other large Sun simulator development programs, not one of which is as yet operational. Without exception, the performance predictions for these large solar simulators have been optimistic. It is apparent, therefore, that full-scale, realistic optical experiments are required.

The fundamental objective of this program has been to obtain well-collimated beams of good uniformity and spectral characteristics, together with improved efficiency. The performance specification for the first application of this new design is as follows:

| | |
|---|---|
| Useful testing volume | 6-ft diameter x 10-ft depth |
| Intensity | 135 w/ft$^2$ minimum |
| Collimation | Worst ray deviation, 2 deg from axis |
| Uniformity | ±5% radially, ±10% in depth |
| Spectrum | Thermal effect on JPL spacecraft (except solar panels), the same as natural sunlight |
| Back reflections | Minimize by off-axis arrangement |

The design was also limited to readily available optical elements so that a full-size demonstration could be performed before commencing the design of a new space simulator.

In September 1962, a preliminary analysis was begun which yielded performance expectations compatible with the new system requirements. A program of feasibility experiments was then undertaken which verified those predictions. The present report covers the work done during this preliminary analysis and feasibility experimentation period: September 1962 through January 1963. Subsequent reports will include the follow-on optimization experiments and the full-scale complete system performance evaluations.

## II. SYSTEM DESCRIPTION

This new design is an integrated system in which each light source illuminates the entire test volume. Flexibility is thereby obtained for mixing light sources to improve the spectral properties and for varying the size, intensity, and collimation characteristics as required for a particular purpose. In addition, the problems of shadow filling in on-axis Cassegrainian systems or beam-matching between modules have been avoided. Since each light source fills the entire beam, time variations in intensity and spectrum can be monitored at a single point while time variations in uniformity are unlikely.

A schematic diagram of the system is shown in Fig. 1, which is drawn out of scale for clarity. Three basic elements are involved:

(1) light source reflector units, which collect and focus energy on the entrance of (2) the mixer, which accepts this nonuniform illumination and optically generates uniform illumination for (3) the collimator, which produces a uniform, collimated beam of light at the test volume.

The unique element of this system is the mixer, which can accept highly nonuniform light and produce uniform illumination efficiently. This mixer consists of two arrays of 19 lenses each. The first set is a tightly packed honeycomb assembly of hexagonal lenses which divide the incident light into 19 channels. These lenses are selected to produce images of the array of source lights which are slightly smaller than the lenses themselves. The second-array lenses are located at this image plane and project each channel of illumination onto the collimator at the proper final beam diameter. The collimator is illuminated uniformly if the incident illumination on the mixer entrance has radial symmetry, since equal and opposite intensity gradients are everywhere superimposed.

The system is described geometrically in Fig. 2, where for clarity only one of the 19 pairs of lenses is shown. The symbol "L" represents the size of the honeycomb lenses element in the mixer entrance, while the symbol "i" is assigned to the size of the image of the source lamp array "L" which is formed by that lens. The symbol "C" is the size of beam illuminating the collimator (the final beam size), while "f" is its focal length. The geometric optical relationships given demonstrate that the cone through which light may enter the system is related to the cone of illumination to the collimator by the ratio i/h, a constant which is slightly less than unity. Rays which are incident upon the mixer entrance but which do not fall within this acceptance cone will not reach the test volume. Now, since the beam size "C" is specified by the test volume diameter and the collimator focal length "f" is chosen to provide acceptable test volume uniformity from uniform incident illumination, the acceptance cone of the system is fixed. For this initial 6-ft-diameter simulator, a collimator focal length of 20 ft was chosen. From this 20-ft focal length it is apparent that the diameter of the second lens array of the mixer, which is located at the focal plane of the collimator, must not be larger than 18 in. in diameter to avoid exceeding the collimation limitation.

Estimates of the energy losses in the above specified portion of the system were now made. These were deliberately chosen to represent the maximum losses indicated by practical experience. The following table of values shows this conservative performance rationale.

1. 6-ft diameter at 135 w/ft$^2$ requires 3.14 x 36/4 x 135/0.83 = 4600 watts in the uniformly illuminated hexagonal beam.
2. Assume 1000 w/lamp delivered on the circle circumscribing the mixer entrance pupil (a value approximately equivalent to experimental efficiencies previously obtained from 5-kw xenon compact arc lamps

and 16-in.-diameter latus rectum ellipsoidal reflectors). The energy per lamp into the system is then 1000 x 0.83 = 830 w/lamp.

3. Estimates of the system element efficiencies are taken to be:

| | |
|---|---|
| 0.80 | 1st lens transmission |
| 0.90 | 1st lens scattering |
| 0.80 | 2nd lens transmission |
| 0.90 | 2nd lens scattering |
| 0.75 | collimator reflectance |
| 0.75 | test volume edge losses |
| 0.29 | total efficiency |

4. Lamps required

$$= \frac{4600 \text{ w}}{\left(\frac{830 \text{ w}}{\text{lamps}}\right) 0.29} = 19$$

An estimation of the effect of lens aberrations on the image size "i" was made, resulting in an acceptance cone which permitted an array of 19 reflectors, each 16 in. in diameter, to be located 35 ft from the mixer entrance.

This analysis, then, defined the dimensional parameters and the subsystem performance requirements necessary to meet the overall system performance specification. The demands seemed well within reasonable expectations, and a program of subsystem evaluations was laid down. The results of these subsystem feasibility programs are described next.

## III. MIXER FEASIBILITY PROGRAM

The only unique feature of this system is the optical "mixer." Therefore, an experiment was immediately undertaken to demonstrate its feasibility. An ellipsoidal reflector was obtained whose latus rectum diameter is 16 in. and whose second focal length is 35 ft. This reflector was mounted near the ceiling in a high-bay building with a 5-kw xenon compact arc lamp and a flat reflector to turn the beam axis horizontally. Inexpensive cast lenses of the approximate required focal length were obtained, trimmed to shape, and mounted in a crude support structure. While these lenses were trimmed to the proper size, their focal lengths were sufficiently off-design so that the hexagonal image produced at the collimator plane was 104 in. across the flats instead of 72 in. Finally, a survey apparatus which could traverse this 104-in. beam was built and was installed at the plane of the collimator. Figures 3, 4, and 5 are photographs of the experimental mixer taken during this test. Since only one lamp and reflector were used, the array image at the second lens is very small. Figure 6 shows the intensity distribution taken at the first lens plane during later tests. Variations of intensity by a factor of 5 are apparent at the mixer entrance. Figure 7 is a survey of intensity taken at the collimator plane with an Eppley pyroheliometer. It can be seen that the division and superposition of 19 segments does indeed produce uniformity within the required limits in the illumination at the collimator. Additionally, the major source of nonuniformity is an increase in intensity at the outer edges of the beam. Analysis of the lenses employed, which were plano-convex, indicated that this effect was probably due to spherical aberration and could be reduced by using a double-convex design. Subsequent experiments (which will be reported in detail later) proved that this was the case. Note also that the edges of this beam are quite crisp even though the lens pairs are coaxial; this means the beams are not precisely superimposed. The edge losses should be very small, and in the final system the lens axes will be adjusted so that the 19 beams are exactly superimposed at the test plane. This superposition will be accomplished by using optical eccentricity, or "wedge," in the second lenses. Superposition can be obtained by this means at any plane selected.

## IV. HEADLAMP FEASIBILITY PROGRAM

The combination of a light source and a collecting reflector is referred to here as a "headlamp" assembly. An ellipsoidal reflector of approximately 4-in. first focus, 35-ft second focus, and 16-in. diameter (a latus rectum ellipsoid) was specially ground and polished from a glass sagging. It was set up with a flat turning mirror as shown in Fig. 8. At the second focus a spiral copper tubing water calorimeter was mounted together with an insulating and reflecting mask which exactly duplicated the entrance pupil of the mixer. This arrangement is shown in Fig. 9. Water flow rates and inlet-outlet water temperature differences were measured to permit calculation of absorbed energy. The reflectance of the turning mirror, ground and polished from "Pyrex," was taken as 0.85. Since this is probably an upper limit it should give a conservatively low figure for collection efficiency. Using a 5-kw xenon lamp, 1080 watts was measured by the calorimeter. This figure is 30% greater than required by the loss analysis given previously. Measurements using a 5-kw Hg-Xe lamp yielded 800 watts, indicating that both kinds of sources will meet the performance, and an optimum mixture can be used to give the best spectral properties. Examination of the lamp manufacturers' data indicates that a mixture of 2 Xe to 1 Hg-Xe will have an effect on JPL spacecraft surfaces which is thermally very close to that of sunlight outside the Earth's atmosphere: closer, in fact, than the illumination from carbon arcs.

A traversing device carrying an Eppley thermopile was also installed at the second focus and intensity surveys were taken. These surveys are shown in Fig. 6. The ordinate spacing on this intensity plot is exactly the size of the mixer entrance lenses: thus, the intensity variation in the various mixer channels can be deduced from this figure. Various other reflectors were examined during this program and several new configurations will be made. These experiments will be reported in a later memorandum. The result of this experiment, however, showed performance well above the requirement limit with existing hardware.

## V. COLLIMATOR FEASIBILITY PROGRAM

The performance of the collimator was attacked analytically to circumvent the cost and delivery problems associated with an 8-ft-diameter reflector. A certain degree of confidence in this approach was felt, since the analytical techniques employed were those used in modifying the 25-ft simulator optical system, a highly successful experiment which performed precisely as predicted.

The analytical technique employed assumed a uniform point source of illumination for each lens in the mixer exit plane. These point sources illuminated the collimator, and the energy distributions across various planes normal to the system axis were determined using a digital computer. Various axial locations of the mixer with respect to the collimator focus were taken. Figure 10 presents the results of the calculation where the mixer exit plane and the collimator focus coincide. The lines of given values of H/F are intensities across the planes located a distance H/F above the reference plane (one focal length below the collimator focus) using a spherical collimator. For the new 10-ft space simulator, the center test plane will be the plane H/F = 1.0, while the planes 5 ft above and below will lie at H/F = 1.25 and 0.75, respectively. This calculation demonstrates that a variation of ±2% will be superimposed upon the intensity variation in the illumination incident upon the collimator. Note that the intensity variation from a parabolic collimator exceeds that obtained from a sphere, although it is the same on every plane. Uniformity within the limits of the specification, then, appears to be obtainable using a spherical collimator.

## VI. CONCLUSIONS

This report has presented a description of the JPL Advanced Solar Simulator Type A, together with the results of analytical and experimental studies verifying its performance at the subsystem level. A program of subsystem optimization is underway which indicates performance capability far beyond that reported here. A complete full-sized system is currently under construction, and final evaluation at the testing volume will be undertaken as soon as possible. These results, as well as those of the subsystem optimizations, will be published when available. Finally, a program of improvement will be undertaken to extract the untaped potential of the system in order to provide large, integrated Sun simulators for use in such applications as the Voyager spacecraft.

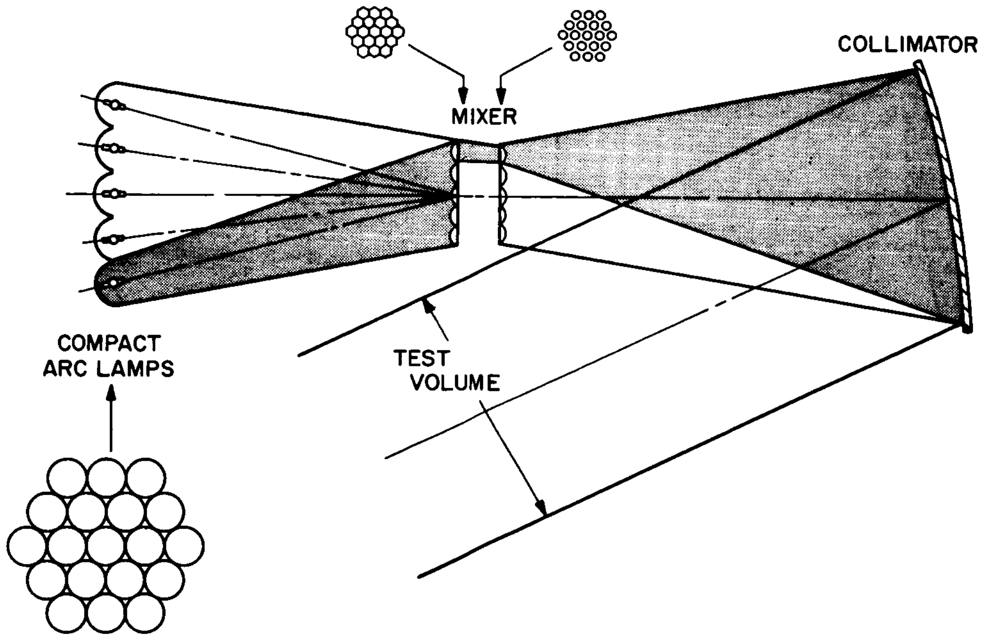


Fig. 1. System schematic diagram

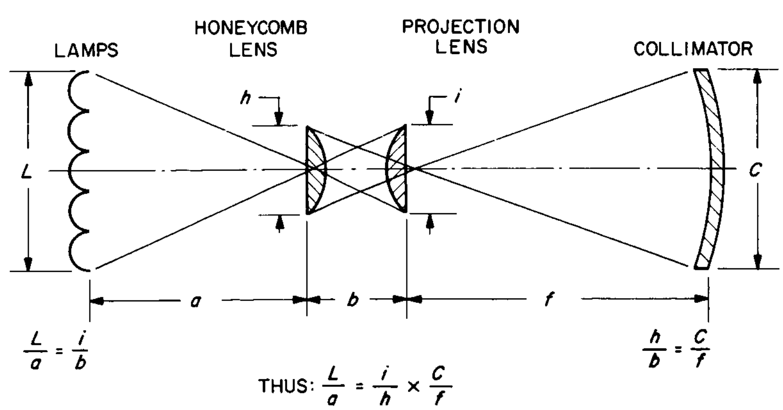


Fig. 2. Geometric relationships

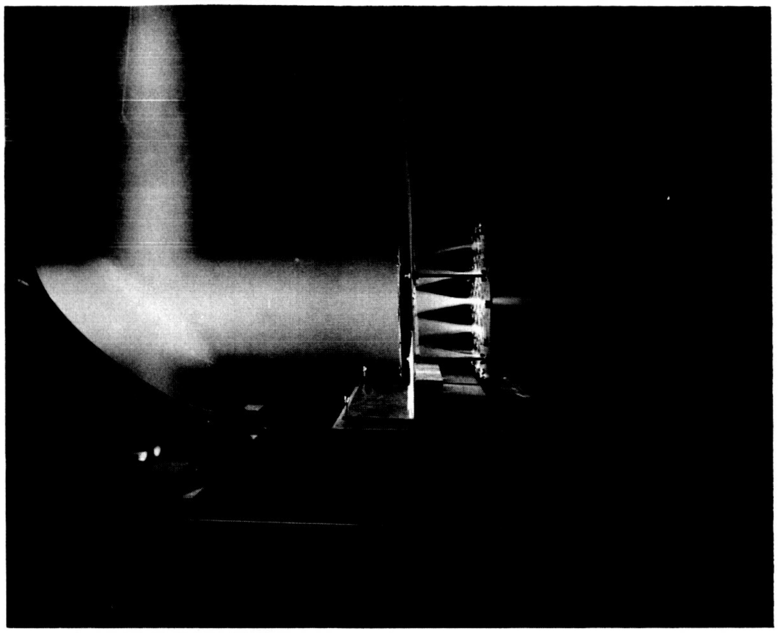

Fig. 3. Mixer, side view

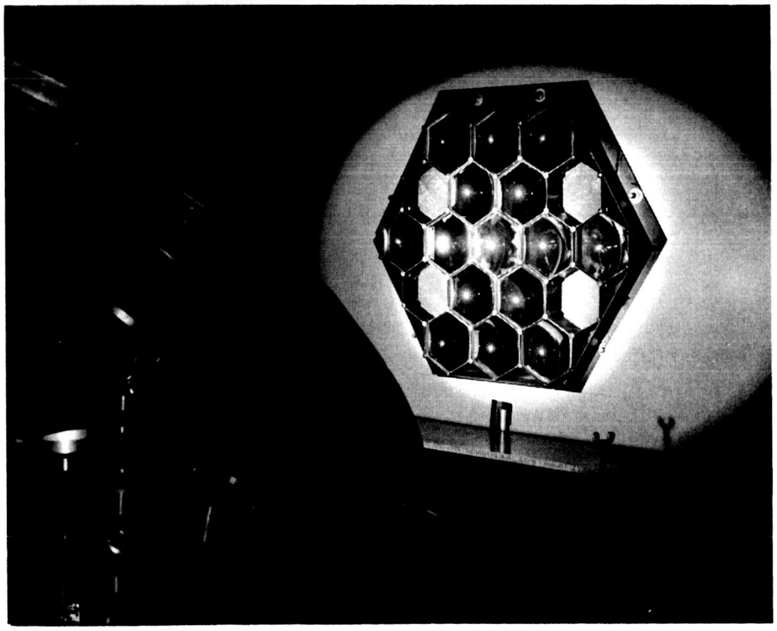

Fig. 4. Mixer, first lens array

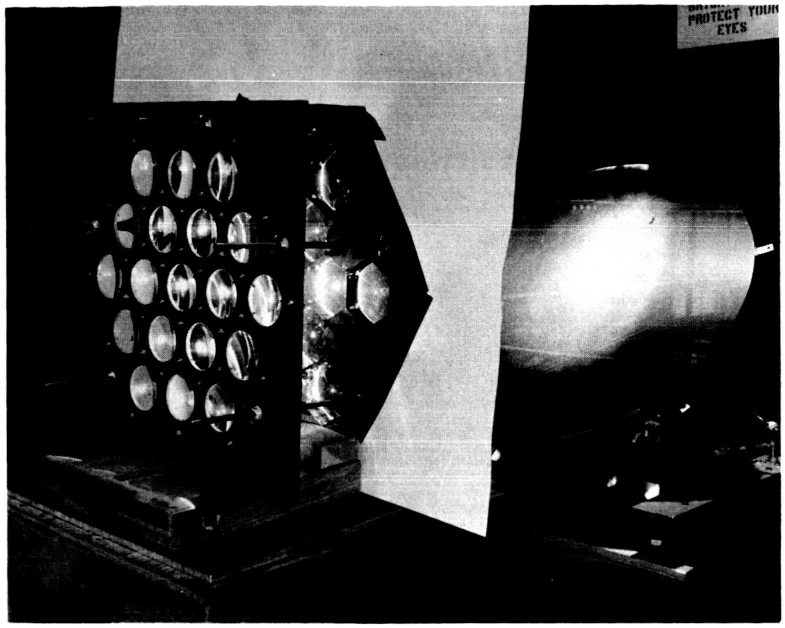


Fig. 5. Mixer, second lens array

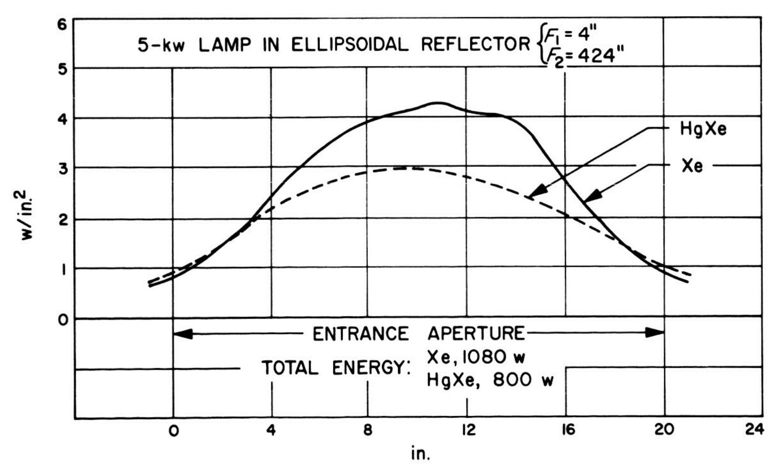


Fig. 6. Intensity distribution at mixer entrance

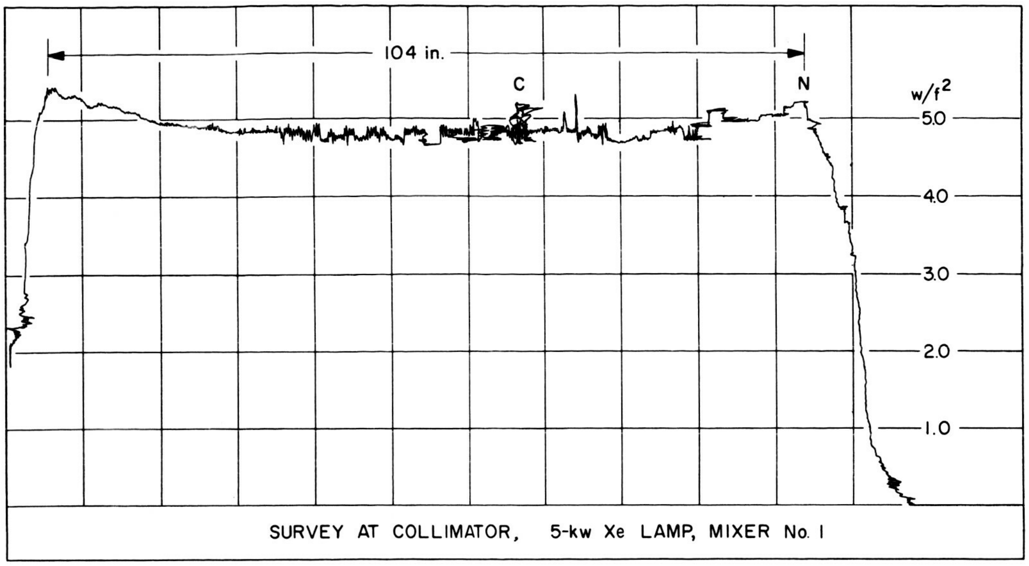


Fig. 7. Intensity distribution at collimator

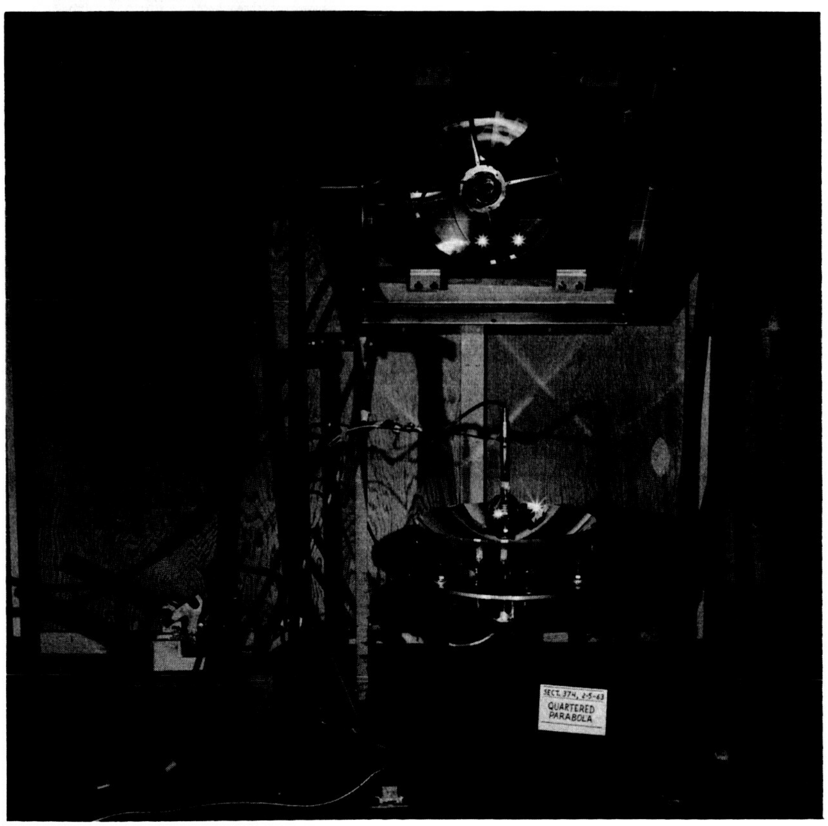


Fig. 8. Headlamp assembly

Fig. 9. Calorimeter and mask

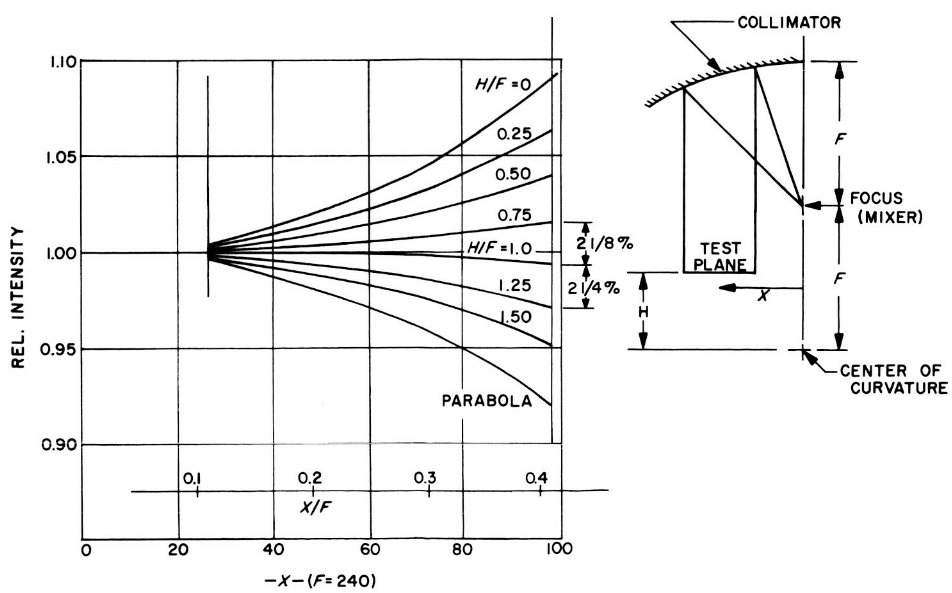


Fig. 10. Intensity distribution in test volume